CHAPTER I

THE MICROWAVE BACKGROUND RADIATION

The Cosmic Microwave Background

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ABSTRACT. This review summarizes recent observational work on the cosmic microwave background, or 3 K radiation. Recent measurements of its spectrum and large-scale angular distribution are described, as well as searches for small angular scale fluctuations on arcsecond to degree scales. A few of the consequences of these measurements and upper limits for cosmology, astrophysics, and theories of galaxy formation are touched on here.

Like many others, I am here in China for the first time. In my three days here so far, I have already seen enough hospitality and energy to hope this trip will not be my last. I would like particularly to thank the Local Organizing Committee and my Chinese colleagues for making me feel so welcome.

My task today is to review observations of the cosmic microwave background (CBR). This radiation, discovered 22 years ago by Arno Penzias and Robert Wilson (1965), was immediately interpreted by Robert Dicke and his colleagues as radiation left over from a hot Big Bang of the Universe (Dicke, Peebles, Roll and Wilkinson, 1965). In this model, the radiation should be approximately isotropic and have a blackbody spectrum.

There are, however, a number of astrophysical processes which may have operated in the redshift interval $10^6 \gtrsim z \gtrsim 3$ to perturb either the spectrum or the isotropy of the radiation. These small epartures from perfect isotropy or an exact Planckian spectrum, if detected, would provide important information about epochs in the Universe not accessible by other observational techniques. I will mention some of these astrophysical processes as I summarize the recent observational results, but my main emphasis will be on the observations. These fall essentially under three main headings:--the spectrum of the CBR, its large-scale anisotropy (especially the dipole component in its intensity), and small-scale anisotropies or fluctuations in the observed temperature of the radiation.

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I intend this to be a very general overview of recent observational results. Several more detailed papers, on measurements of the dipole anisotropy, the spectrum, and intermediate and fine-scale anisotropies, follow this review. I should also mention that much of the material I present here has been drawn more or less directly from a long review paper I prepared at about the same time as this IAU symposium (Partridge, 1987). Since that review and other recent overviews of the field are available (e.g., Wilkinson, 1986; Partridge, 1986), I will omit in this written version of my remarks much of the detail I presented orally in Beijing. In particular, I will devote considerably less attention here to measurements of the angular distribution of the radiation.

1. SPECTRUM

Early measurements of the spectrum of the microwave background (as reviewed, for instance, by Wilkinson, 1980; Richards, 1980; or Weiss, 1980) showed that the spectrum was on the whole consistent with a Planck curve of temperature 2.5–3.0 K. However, measurements made by Woody and Richards (1981), using a bolometric detector flown above much of the earth's atmosphere, suggested a departure from a blackbody curve near the peak of a 2.5–3.0 K spectrum. The nature of the departure is shown in the cartoon diagram below. Considerable theoretical energy (e.g., Negroponte et al, 1981; Bond et al, 1986) went into offering explanations for the ~ 10 percent increase in temperature or intensity at wavelengths of a few millimeters.

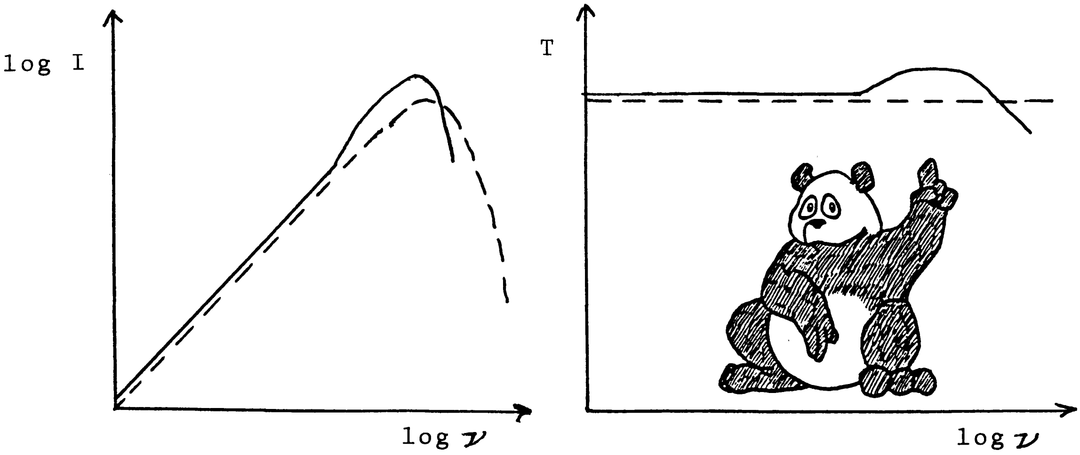

Figure 1. Schematic representation of the intensity and of the thermodynamic temperature of the CBR as determined by observations prior to 1982. The panda indicates the apparent departure from a Planck curve.

By the early 1980's, improved experimental techniques had made refined measurements of the spectrum possible and had allowed us to test the findings of Woody and Richards. In the past five years, a number of groups have worked to improve measurements of the spectrum of the background radiation over a wavelength range of more than 100, from $\lambda = 12$ cm to $\lambda \simeq 1$ mm.

1.1. Sampling the CBR temperature using interstellar molecules.

Interstellar CN (cyanogen) molecules have low-lying rotational energy levels which can be excited by photons at wavelengths of 2.64 and 1.32 mm. Measurements of the relative populations of these levels can thus tell us the thermodynamic temperature of the microwave radiation field in space at these two wavelengths. The relative populations, in turn, may be determined by measuring the equivalent width of optical lines originating on these low-lying levels---see figure 2. As the figure suggests, these observations are made in absorption, using a bright star as a background source. Two groups, Meyer and Jura (1984, 1985) and Crane et al (1986) have made use of this technique to redetermine the temperature of the microwave background at 2.64 and 1.32 mm. The work of the latter group is described in more detail here by one of the members of the collaboration, Dr. Mandolesi. Here, I merely summarize the observational results in Table 1. Note that the measurement at 2.64 mm, near the peak of the 2.5-3.0 K blackbody spectrum, is the single most accurate measurement we have of the temperature of the CBR.

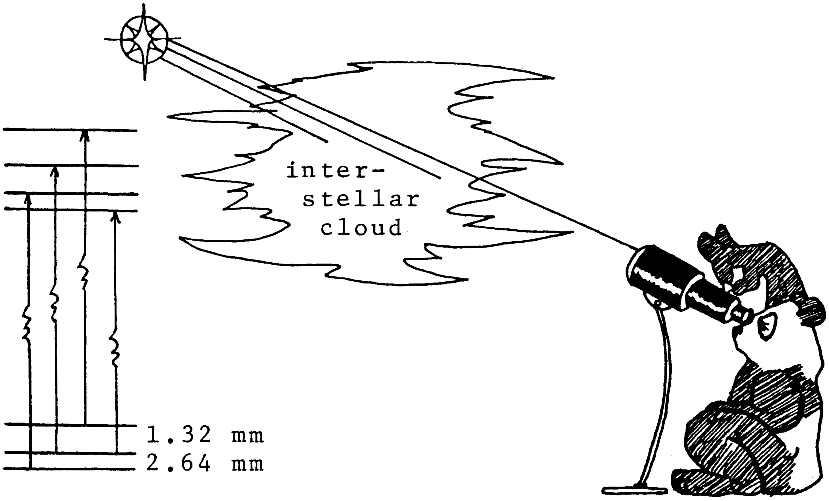

Figure 2. Sketch of the means used to measure the CBR temperature using the excitation of interstellar CN molecules.

Observers	T, λ = 2.64mm	T, λ = 1.32 mm
Meyer and Jura (1984)	2.73 ± 0.04	2.8 ± 0.3
Crane et al (1986); see Mandolesi here	2.74 ± 0.05	2.75 ± 0.3

Table 1. Measurements of the CBR temperature using CN molecules.

1.2. Long wavelength measurements.

More precise measurements of the spectrum in the Rayleigh-Jeans region were undertaken in 1982 and 1983 by an international collaboration of astronomers from Bologna, Milan, Padua, Berkeley and Haverford. The results are fully described in Smoot et al (1985) and in review papers that I have prepared (1986, 1987). The final results of this collaborative work are displayed in both Table 2 and Figure 3. I note here that the experiment was specifically designed to ensure good intercomparability of measurements made at different wavelengths. For instance, the same antenna design was used for measurements at all five wavelengths, and the cold-load calibrator was common to all. In addition, we devoted considerable attention to the measurement of sources of systematic error, such as emission from the Galaxy, the ground and the earth's atmosphere. The magnitude of some of these are indicated in Table 2. While the emphasis was on relative accuracy within our set of five measurements, it is gratifying to see how well they mesh with the CN measurements referred to above.

Wavelength, cm	Atmos. Temp.	Galactic Emission	T CBR
12	0.95	0.15-0.20	2.77 ± 0.13
6.3	1.00	~ .04	2.70 ± 0.08
3.0	1.14	< .01	2.75 ± 0.08
0.9	4.5-4.9	~ 0	2.81 ± 0.12
0.33	10-13	~ 0	2.57 ± 0.14

Table 2. Radiometric measurements of the CBR temperature (Smoot et al, 1985). The weighted means of 1982 and 1983 measurements are shown. The atmospheric temperature at 0.9 and 0.33 cm depended on the water vapor content of the atmosphere--approximate values are indicated.

Because the equipment employed was cumbersome, this experiment was necessarily ground-based. We were thus faced with the problem

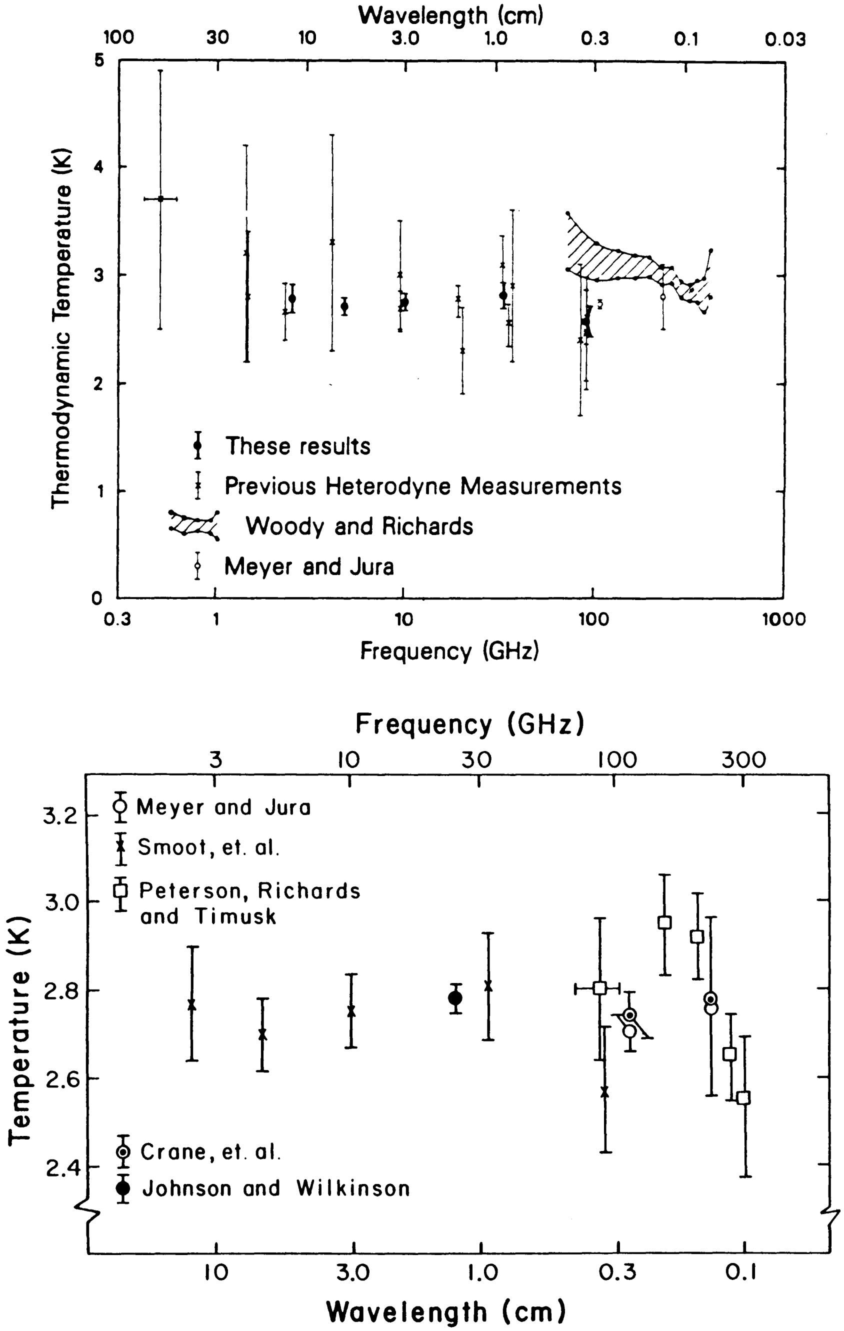

Figure 3. (Top) Measurements of the spectrum of the CBR available by early 1985 ("These results" = Smoot et al, 1985). (Bottom) Recent spectral measurements discussed here.

of measuring accurately and subtracting microwave emission from the earth's atmosphere (Partridge et al, 1984; Danese and Partridge, 1987). Another approach to the problem presented by emission from the earth's atmosphere is literally to rise above it, as Johnson and Wilkinson (1986) did by flying their instrument on a balloon. At an altitude of ~ 25 Km, the residual emission of the earth's atmosphere is easily corrected for. Their measurement was made at a wavelength of 1.2 cm. That experimental result is presented in poster form here; the authors give two possible errors, a formal statistical error and a more conservative error. Using the latter, they find at a wavelength of 1.2 cm, $T = 2.78 \pm 0.08$ K, once again in excellent agreement with all the recent results described so far.

1.3. Measurements near the peak of the spectrum.

Finally, Richards and his colleagues have repeated their observations near the peak of a 2.5–3.0 K blackbody spectrum, in the wavelength range $5 \gtrsim \lambda \gtrsim 1$ mm. They again used a broad-band, bolometric detector. For the most recent observations, however, they employed filters to define five wavelength bands in the range of wavelengths noted above, and the instrument was calibrated in flight. The results of these new observations (Peterson, Richards and Timusk, 1985) are also shown in Figure 3. While there is still some barely significant evidence for a slight increase in the temperature of the CBR just at the peak, that is, around 2 mm, the overall results are now in excellent agreement with the cyanogen measurements which fall in the same wavelength range.

1.4. Summary of spectral measurements.

To summarize, over a wavelength range extending from 0.1 to 12 cm, right across the peak and well into the Rayleigh-Jeans region of a 2.5–3.0 K spectrum, there is no evidence for spectral distortions. Taken together, the measurements establish the temperature of the CBR at 2.75 K with an accuracy of ~ 1 percent--in my view an important baseline in astrophysics.

1.5. Consequences.

Let us now look briefly at some of the consequences of the recent measurements summarized above.

First, the fact that the observed spectrum of the CBR is so close to blackbody is hard to explain in models which invoke re-emission by hot dust to explain some or all of the microwave background (e.g., Negroponte et al, 1981). Very special optical properties of the dust would have to be assumed to make the observed temperature constant over so wide a range of wavelength.

The observational results also place interesting limits on any sort of energy release into the microwave background over a redshift range of order $10\text{–}10^6$ (see review by Danese and De Zotti, 1977). Adding energy to the radiation field would perturb the spectrum; the absence of evident spectral distortion limits the energy release, ΔE, to $\lesssim$ 5 percent of the energy density of the CBR. For instance, the energy released in the process of galaxy formation cannot exceed this limit. Likewise, the energy released by the decay of possible exotic particles cannot exceed this limit, hence placing limits on the physical parameters of such particles (e.g., Silk and Stebbins, 1983). I could continue with a catalog of other ways in which the absence of evident spectral distortion has been used to set limits on astrophysical processes occurring at these large redshifts; instead I will just remark that I feel the power of this constraint has not been fully recognized or employed. I hope some of you present here will take up the challenge that this remark implies.

Finally, a value for the present temperature of the CBR is one of the parameters needed to calculate the relative abundances of light nuclei synthesized in the Big Bang, as reviewed in this volume by Prof. Audouze. The error in the value of the CBR temperature is now negligible compared with other uncertainties in this calculation. A slightly subtler point is that the absence of spectral distortions permits us to assume with more certainty that the temperature we now measure can be directly related to the temperature prevailing at the much earlier epoch of nucleosynthesis.

2. LARGE-SCALE ISOTROPY

Early measurements of the large-scale angular distribution of the CBR showed it to be isotropic to a few percent, as expected in the Big Bang model of Dicke et al (1965). These observations, reviewed by Weiss (1980) and elsewhere by the present author (1987), were thus in agreement with the predictions of the Big Bang model. But it has been known for 20 years that large-scale anisotropy in the radiation may be introduced in two general ways. The first of these is motion of the observer; the Doppler effect ensures that in the direction of motion the intensity of the CBR, and hence its measured temperature, will be slightly increased. The Doppler effect introduces a dipole component into the measured temperature of the CBR. A second cause of large-scale anisotropy is anisotropic expansion of the Universe as a whole. In the simplest case, a pure quadrupole component would result, but other possibilities including temperature anisotropy on an angular scale of $\sim \theta \simeq \Omega$ radians are also possible in open Universes with $\Omega \equiv \rho_O/\rho_C < 1$. Some of these possibilities are mentioned briefly in the review by Dr. Lukash here and also in Barrow et al (1983).

2.1. Recent observational results.

Just as in the case of spectral measurements, measurements of the large angular scale distribution of the CBR have been improved in the past few years. Four groups have worked on these measurements. The results obtained by three of these groups are summarized in Table 3 below. The Berkeley and Princeton groups employed radiometers carried aloft by balloons; the results of the Soviet group were obtained from the first satellite devoted to measurements of the CBR, the Relict experiment on the Prognoz 9 satellite. The fourth group that has made such measurements is based at MIT. Since their measurements are made at quite short wavelengths, they cannot be directly compared to measurements made at wavelengths longer than the peak of a 2.5-3.0 K blackbody unless the temperature of the CBR is known accurately. Therefore, the MIT group has used their results to obtain estimates of both the dipole component and the temperature of the CBR, and these results are described in detail in the following paper by Dr. Halpern.

Group	Berkeley	Princeton	Moscow*
Reference	Lubin et al (1983)	Fixsen et al (1983)	Strukov and Skulachev (1984)
λ, cm	0.3	1.2	0.8
dipole amplitude	3.4 ± 0.2 mK	3.1 ± 0.2 mK	3.16 ± 0.12 mK
direction of sun's velocity	$11^h.5$, -6°	11^h, -10°	$11^h.3 \pm 0^h.15$, $-7.5^\circ \pm 2.5^\circ$

*Updated results from the paper of Lukash here.

Table 3. Results of three recent measurements of the dipole component of the CBR (see the following paper by Halpern for the fourth such measurement). The three measurements above imply a velocity of the local group of galaxies of $V_{LG} \sim 600$ km/sec towards $\ell = 270^\circ$, $b = 30^\circ$ in Galactic coordinates.

Returning to the longer wavelength measurements summarized in Table 3, note the excellent agreement on the dipole amplitude. In particular, the re-analysis of the Prognoz 9 results reported here by Dr. Lukash gives a larger value for the dipole amplitude than that reported earlier by Strukov and Skulachev (1984), one in better agreement with the other measurements. If we interpret the dipole amplitude as a consequence of the Doppler effect, we can determine the direction of the motion of the sun (neglecting the small motion of the earth around the sun); we can then correct this value for the known motion of the sun around the center of the Galaxy, and the motion of the Galaxy in the local group, to provide an estimate of the velocity of the local group itself. That value is something like 600 Km/sec in the direction 270° galactic longitude and 30° galactic latitude. While there is some uncertainty in the sun's motion relative to the local group (somewhat larger than the experimental uncertainty in the CBR dipole), the qualitative conclusions of these measurements are not affected. They show that the local group is moving with a substantial velocity, ~ 0.002 c, and that the direction of this motion is at ~ 45° to the direction to the center of the nearest large concentration of mass, the Virgo cluster.

The same observational programs that have determined the dipole component of the CBR may also be used to establish upper limits on the quadrupole component. Earlier reports (e.g., Fabbri et al, 1980; Boughn et al, 1981) of a quadrupole component of amplitude ~ 1 mK appear to be in error; the present upper limits on the quadrupole component are $\Delta T/T \leq 3 \times 10^{-5}$, the most sensitive upper limit resulting again from a reanalysis of the Soviet satellite observations (additional details provided in the paper here by Lukash).

Since most of these observational results are now several years old, and in any case are discussed in review articles (Wilkinson, 1986; Partridge, 1987), I will turn now to a discussion of some of the consequences of these findings. In the remainder of section 2, I want to focus on three points:--a comparison of the velocity inferred from CBR measurements with that derived from optical measurements; a discussion of the possible causes of the dipole component; and consequences of the apparent absence of true, cosmological, anisotropy.

2.2. Comparison to optical results.

The microwave dipole component provides, as we have seen, a measure of the velocity of the local group relative to matter at large distances. The velocity of the local group may also be determined by making observations of the distribution of redshifts of more local objects. A decade ago, Dr. Rubin and her colleagues (Rubin et al, 1976) began a program of optical measurements of the redshifts of a shell of galaxies centered on us. By determining the systematic variations of redshift across the sky, they were able to deduce the velocity of the local group. The speed they determined was roughly comparable to the 600 Km/sec figure mentioned above, but the direction was approximately orthogonal to the microwave result. Since those results were announced, there has been considerable discussion and even controversy about the optical results and further measurements (see, e.g., Fall and Jones, 1976; Schechter, 1977; deVaucouleurs and Peters, 1984; Yahil et al, 1986; and Meiksin and Davis, 1987). I have elected to skip over most of that material and move to a very recent--and also controversial--paper on this subject (Collins et al, 1986). Using a different technique to determine the distance to some of the galaxies used originally by Rubin and her colleagues, these authors find results in good agreement with the original 1976 work. They therefore make the suggestion that both the optical and the CBR results are experimentally correct. If so, we must infer that the shell of galaxies observed by Rubin and her colleagues is in rapid motion with respect to matter at large distances. This indeed is the claim of Collins et al--velocities of 1000 km/sec on megaparsec scales are present in the Universe. As Collins et al (1986) note, such large-scale and substantial velocities are very difficult to reconcile with models in which the density of the Universe and the process of galaxy formation are dominated by cold dark matter. These issues are discussed later in this volume by Drs. Dekel and Silk, among others.

2.3. Gravity as a cause of the microwave dipole.

A further consequence of the assumption that both the microwave and the optical velocity measurements are correct is that it is quite difficult to say exactly what produces either of them. The simplest assumption is that a large, localized, lump of matter induces the velocity of the local group by gravitational attraction. If that were true, and if the local lump lay well inside the shell of galaxies used for the optical observations, then the optical and microwave results should agree. Under the assumption that the microwave and optical results are both correct, therefore, the situation must be more complex. For now, however, I wish to put this reservation aside to sketch out some of the consequences of the simpler assumption that a single large lump induces gravitational acceleration, producing the observed dipole component.

If the observed dipole component of the microwave background is gravitationally induced, we may use its amplitude to tell us something about the large-scale distribution of matter in the Universe and even to estimate the mean mass density, ρ_O. As an example of this sort of calculation, I will assume that the accelerating lump has spherical symmetry, and that its center is located a distance r away from us. If we neglect nonlinear effects, the gravitationally induced velocity as a fraction of the recession velocity is given simply by:

$$V/H_O r = \frac{1}{3}\,\bar{\delta}\,(\rho_O/\rho_C)^{0.6}$$

where $\bar{\delta}$ is the overdensity of the local lump. To a first approximation, we may determine $\bar{\delta}$ simply by counting up galaxies. For instance, the overdensity in numbers of the Virgo cluster is ~ 2. If we use this value, and set r equal to the distance to the Virgo cluster, we obtain $\rho_O/\rho_C \approx 0.3 \pm 0.2$. But there are good theoretical reasons for believing that the matter in the Universe may be more smoothly distributed than the light, as measured by counts of galaxies. If that is true, the overdensity $\bar{\delta}$ is smaller than the value inferred from galaxy counts alone, and higher values of ρ_O are possible; indeed the possibility that ρ_O is equal to the critical density ρ_C can by no means be excluded.

Some of these issues are discussed in this volume by Drs. Yahil and Rowan-Robinson and in more detail in a review paper by Davis in IAU Symposium 117 (Davis, 1987). Here I want only to emphasize that one must use some caution in interpreting the microwave results until the apparent discrepancy (if any) with the optical results is resolved. This, too, is an area where further work, both observational and theoretical, is needed. The microwave observers have told us with a precision of a few percent how we are moving relative to matter at large distances; what can we make of this result?

2.4. Intrinsic anisotropy of the Universe.

If the observed dipole component of the CBR is interpreted as a result of the Doppler effect, any residual dipole moment is very small, like the quadrupole component. Taken together, these results imply that the expansion of the Universe has been isotropic and shear-free for the vast majority of the history of the Universe, from the time that the microwave photons last interacted with matter until the present. As pointed out nearly 20 years ago, originally by Thorne (1967) and Hawking (1969), limits on large-scale anisotropies in the CBR can be used to fix quite stringent limits on the anisotropic expansion of the Universe for many classes of spatially homogeneous, but anisotropic, cosmological models (see a recent discussion by Barrow et al, 1983). One possible escape from these conclusions is opened up by some low density anisotropic cosmological models in which the anisotropy is effectively "squeezed" into a small solid angle of the sky of angular dimension $\theta \sim \Omega$ radians (Novikov, 1968; see also the paper by Lukash here). In this connection, the upper limit of $0.004(\mathrm{mK})^2$ placed on $[\Delta T/T]^2$ over the whole sky by the Prognoz 9 experimenters (and reported here by Lukash) is particularly interesting. This limit applies for angular scales $\gtrsim 20^\circ$, and effectively constrains the anisotropy in any cosmological model with $\rho_0 \gtrsim 0.3\ \rho_c$. Fixsen et al (1983) have reported somewhat less sensitive upper limits, but on scales reaching down to 10°, corresponding to $\rho_0 \simeq 0.16\ \rho_c$.

2.5. Summary.

Provided we interpret the dipole component as the result of gravitationally induced velocity, there is no evidence in any of the recent observations for any true, cosmological, anisotropy in the CBR on angular scales of tens of degrees or larger. These results, taken in conjunction with the spectral measurements discussed in section 1, show that the cosmic background radiation is isotropic and blackbody to high precision, just the properties expected if it is a relic of a hot Big Bang phase in the history of the Universe.

3. SMALL ANGULAR SCALE FLUCTUATIONS IN THE CBR TEMPERATURE

In addition to possible large-scale anisotropy in the CBR, smaller angular scale anisotropies or fluctuations may be present. To understand their origin, we must ask where the photons of the CBR we detect originate. While the CBR photons are produced early in the hot Big Bang explosion of the Universe, we cannot see all the way back to arbitrarily early epochs. Instead, the photons we detect here on earth originate at some surface of last scattering, as indicated in the cartoon below. A useful physical analogy is looking at a cumulus cloud. Inside the cloud, optical photons are frequently scattered, so the cloud is opaque and we have no information about its internal

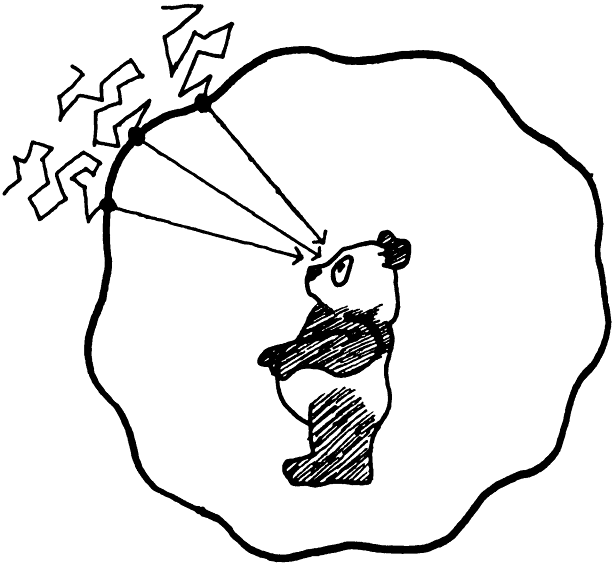

Figure 4. The role of the surface of last scattering. We get no information about the angular distribution of the radiation beyond that surface (i.e., at larger redshifts).

structure. Once optical photons reach the edge of the cloud, they may travel freely towards us through the transparent atmosphere. Hence we see only the cloud's surface, that is the surface of last scattering. In the case of the CBR, the primary scattering mechanism is Thomson scattering from free electrons. Before the matter of the hot Big Bang cooled to a temperature of ~ 3000 K at z ~ 1000, the material contents of the Universe were ionized, and the plentiful free electrons ensured that Thomson scattering was strong. Hence one well defined surface of last scattering was present at a redshift of ~ 1000, when free electrons combined with protons to form neutral hydrogen. For the moment, let us adopt that epoch as the time of last scattering.

Now if the matter of the Universe was inhomogeneously distributed at the epoch of last scattering, small temperature fluctuations in the CBR will result. Unfortunately the connection between the degree of density inhomogeneity $\Delta\rho/\rho$ and the temperature fluctuations $\Delta T/T$ is both complex and model dependent. The very model dependence, of course, makes the observational results so interesting--we have in principle a means of checking our theories of the formation of large-scale structure in the Universe by making straightforward, if difficult, radio astronomical observations from earth.

In this overview, I will focus on three angular scales. The first is an angular scale of a few degrees or so, corresponding to the scale of the causal horizon at z = 1000, which for the moment I take to be the redshift of the surface of last scattering. The second is an angular scale of a few arcminutes. Detailed calculations (for instance by Bond and Efstathiou, 1984; and Vittorio and Silk, 1984) suggest that the maximum amplitude of $\Delta T/T$ fluctuations should be on roughly this angular scale if the surface of last scattering is at about 1000. These same calculations indicate that the amplitude of temperature fluctuations should fall sharply at angular scales below a few arcminutes. If fluctuations are in fact found on angular scales $\lesssim 1'$, they are then most likely due to reionization of the material contents of the Universe which shifts the surface of last scattering to substantially lower redshifts than 1000 (Hogan, 1980, 1982, 1984; Ostriker and Vishniac, 1986).

3.1. Measurements on scales of a degree or more.

A recently reported search for fluctuations in the CBR at a wavelength of 3 cm (Mandolesi et al, 1986) has established an upper limit of $\sim 5 \times 10^{-4}$ on $\Delta T/T$ on scales $\gtrsim 2^{\circ}$. Earlier work on angular scales larger than a degree or so, the causal scale for last scattering at $z \simeq 1000$, are discussed briefly by me elsewhere (1987). Newer observational results, obtained at a wavelength of 3 cm, are described in a paper in this volume by Dr. Davies of Jodrell Bank. The results he reports are at an angular scale of 8°. All of these results show that the Universe is clearly quite homogeneous on these scales. That fact requires some explanation. In the case of the classical Big Bang picture, the only plausible explanation is that the homogeneity of the Universe was ensured by initial conditions, since no causal process could have produced homogeneity on scales larger than the light horizon at $z \simeq 1000$, corresponding in scale to a few degrees. A period of inflationary expansion early in the history of the Universe, however, does provide a convincing physical explanation for the observed homogeneity on these scales, as first noted by Guth (1981, see also his 1986 review). Parenthetically, changing the redshift of last scattering to a smaller value does not change the thrust of these arguments; the angular scale corresponding to the causal horizon becomes larger, say 10°, but an explanation for the observed homogeneity of the Universe is still required.

3.2. Upper limits on $\Delta T/T$ on scales of a few arcminutes.

Over the past decade, most observational and theoretical attention has been focused on anisotropies in the CBR on scales of a few arcminutes. The most interesting and sensitive upper limit yet published is the one set at a wavelength of 1.5 cm by Uson and Wilkinson (1984, 1985). They used the 140-ft. telescope of the National Radio Astronomy Observatory in Green Bank, West Virginia, which has a beam size of 1.5' and a beam switch angle of 4.5'. Their experimental technique permitted them to sample temperature differences between pairs of points separated by 4.5'. A dozen such pairs were sampled. Their statistical analysis of the data established an upper limit of $\Delta T/T \leq 2.5 \times 10^{-5}$ on this angular scale. Subsequent analyses by others have suggested that the data can more reasonably set upper limits of $\Delta T/T \lesssim 5 \times 10^{-5}$. In any case, these results set extremely stringent limits on temperature fluctuations in the CBR, and hence on density perturbations on the surface of last scattering.

A somewhat similar experimental program, at the same wavelength, is being conducted by Dr. Readhead and his colleagues at the California Institute of Technology. No results have yet been published, although some preliminary results are being discussed privately, and the first published results should soon be appearing. The sensitivity is comparable to or perhaps better than that attained by Uson and Wilkinson. One result that has now made the transition from "rumor" to "lore" is a single sample difference $\Delta T/T = (2.5 \pm 8) \times 10^{-6}$. This is the difference in temperature between the north celestial pole and a concentric circle a few minutes of arc away. Although it is a bit like asking Zen question, "What is the sound of one hand clapping?", attempts have been made to use this single difference to establish limits on the statistical properties of temperature fluctuations in the CBR. The resulting upper limits, of course, depend very much on one's assumption about the spectrum of CBR fluctuations, but upper limits in the range of a few times 10^{-5} are being quoted.

Perhaps the most useful thing I can say is that rigorous and sensitive upper limits on $\Delta T/T$ are now available and may soon be pushed even lower, and that these limits are on precisely the angular scales where the maximum fluctuation amplitude in $\Delta T/T$ is expected in models in which the surface of last scattering is at $z \simeq 1000$.

3.3. Search for fluctuations on scales $\lesssim$ 1'.

Let us now drop the assumption that the surface of last scattering corresponds to the epoch of recombination, at $z \simeq 1000$. If the matter contents of the Universe are reionized at lower redshifts, free electrons will again be plentiful, and Thomson scattering will result. The surface of last scattering of the CBR can be shifted to redshifts as low as about 15 (at lower redshifts, even complete re-ionization will produce an optical depth in Thomson scattering well below unity). If the surface of last scattering is shifted to lower redshifts, all information about anisotropy introduced at earlier times is lost. In particular, the arcminute scale fluctuations suggested by the theoretical work of Bond and Efstathiou (1984) or Vittorio and Silk (1984) will be erased. On the other hand, matter in the Universe cannot be exactly homogeneously distributed at these more recent epochs either, and hence new temperature fluctuations will be imprinted on the CBR (see Hogan, 1980 and 1982; Ostriker and Vishniac, 1986; for example). One of the intriguing predictions of these authors is that fluctuations on angular scales less than an arcminute may predominate, unlike the case discussed above.

To make observations of the CBR on scales below an arcminute requires a new observational technique, the use not of a single radio antenna, but an array of antennas. Signals received by an array of radio telescopes are coherently combined to produce a two-dimensional map of the sky with angular resolution corresponding to the size of the array, not the diameter of a single antenna. The advantages and disadvantages of this observing technique are discussed by Fomalont et al (1984a), Knoke et al (1984) and Partridge (1987). Observations made using an array of 27 telescopes, the Very Large Array of the National Radio Astronomy Observatory in New Mexico, operating at 6 cm wavelength, have reached sensitivities in $\Delta T/T$ of 10^{-4} or better on angular scales $\lesssim$ 1'.

Briefly, the technique employed (Fomalont et al, 1984a; Knoke et al, 1984) was to use the array first to make a map of the sky in a region free of bright discrete sources. The remaining visible discrete sources were then removed from the map, and the noise properties of the remaining, nominally source-free, map were then examined. Essentially, we compared the rms noise level at the center of such a map to the noise level near its edges. At the center of the map, where the response of the individual elements of the array is large, the variance contributed by fluctuations in the CBR (or, of course, by faint discrete sources) will be at a maximum. On the other hand, near the edges of the map where the diffraction power patterns of the individual elements of the array have fallen to zero, the noise will be completely dominated by instrumental and atmospheric contributions. Thus a subtraction provides an estimate of the excess variance produced by the sky. This value, in turn, can be corrected for the contribution due to sources too weak to detect individually. The result is an estimate of, or upper limit on, fluctuations in the CBR. Table 4 shows the results of such an analysis. The results are presented as upper limits on $\Delta T/T$. Our own most recent work (Martin and Partridge, 1986) suggests the presence of true sky fluctuations at a level of 1-2 x 10^{-4} on angular scales θ = 18"-60". This value has been corrected for weak discrete sources by extrapolating direct

Reference	Angular Scale	Upper Limit on $\Delta T/T$ x 10^{-4}
Fomalont et al (1984a)	18"	10
	30"	8
	60"	5
Knoke et al (1984)	6"	32
	12"	17
	18"	12
Martin and Partridge (1987)	18"- 80"	~ 2
	36"-160"	~ 1.5

Table 4. Upper limits on small-scale fluctuations in the CBR. All results are from the VLA at λ = 6 cm. As noted in the text, the results of Martin and Partridge (1987) are tentative; Fomalont and his colleagues also have new measurements (see Wall's paper here).

source counts at $\lambda = 6$ cm and 21 cm (Fomalont et al, 1984b; Partridge et al, 1986; and Condon and Mitchell, 1984; Windhorst et al, 1985, respectively). On the other hand, I must caution you that Dr. Martin and I have not yet eliminated all possible sources of instrumental error. It happens that Dr. Fomalont and his colleagues, including Jasper Wall, have now made more extended observations of a different region of the sky and see roughly comparable results. Those results will be reported here by Dr. Wall, but I believe it is true to say that the analysis of their results is not complete either. Nevertheless, we have here a tantalizing hint that anisotropies in the CBR may have been detected. What is more interesting, if these results hold up, is that fluctuations in the CBR are apparently most visible at the "wrong" angular scale, a factor of 10 smaller than expected from models of temperature fluctuations induced by density perturbations at the epoch of recombination (Bond and Efstathiou, 1984; Vittorio and Silk, 1984).

3.4. Summary.

Nearly two decades of effort have gone into searches for anisotropies in the CBR on angular scales of a few arcseconds to many degrees. As the papers by Davies and Wall in this volume suggest, we may be on the verge of detecting CBR fluctuations for the first time. Even if these observational results hold up, however, the main outcome of these two decades of effort has been to show how smooth and featureless the microwave background truly is. The upper limits on $\Delta T/T$ have already had a decisive influence on theories of the formation of large-scale structure in the Universe (see Silk's review here). I turn to some of the consequences of these observations next.

3.5. Consequences of upper limits on $\Delta T/T$.

If the CBR is observed to be isotropic on angular scales larger than the causal horizon scale, as it appears to be, then either large-scale homogeneity has to be assumed as an initial condition, or some physical cause for it is required. As noted above, inflationary expansion of the Universe can produce just the kind of large-scale homogeneity we see. Thus the observations summarized under 3.1 above support the introduction of an inflationary phase into standard Big Bang cosmology.

The upper limits on arcminute scales can tell us much more. To interpret these upper limits, however, requires an assumption about the surface of last scattering. If we take it to correspond to the epoch of recombination, $z \simeq 1000$, then the absence of detectable CBR fluctuations allows us to set limits on the density inhomogeneity at that crucial epoch. The most straightforward theoretical possibility for the formation of galaxies and other large structures is that they form from adiabatic perturbations in pure baryonic matter. This possibility is effectively ruled out by the CBR results, especially the measurement of Uson and Wilkinson (1985). As a consequence, most aspects of this simplest picture have been modified in one way or another to attempt to fit the observational constraints. First, the notion that the inhomogeneities are adiabatic, that is that both the matter and the radiation content of the Universe are perturbed, has been dropped in favor of isothermal perturbations, in which the radiation, to first order, is not perturbed. This change can reduce the predicted amplitude of ΔT/T fluctuations by approximately an order of magnitude (in baryonic matter models [Davis and Boynton, 1980], but see Efstathiou and Bond, 1986). Second, both to make models of galaxy formation conform with the CBR upper limits and for other more direct reasons, additional forms of matter have been introduced into cosmology, known generically as "dark matter." These include neutrinos with nonzero rest mass and various forms of cold dark matter, possibilities touched on by other speakers at this symposium. Since these nonbaryonic forms of matter couple less strongly to the radiation field, it is possible to accommodate larger density perturbations in them for a given upper limit on ΔT/T. Galaxy formation then occurs when the more tightly coupled baryons decouple from radiation and fall into the gravitational potential wells established by the neutrinos, cold dark matter, or what have you. Nevertheless, as Figure 5 shows, even some of these models find themselves in trouble with the observational upper limits. As a

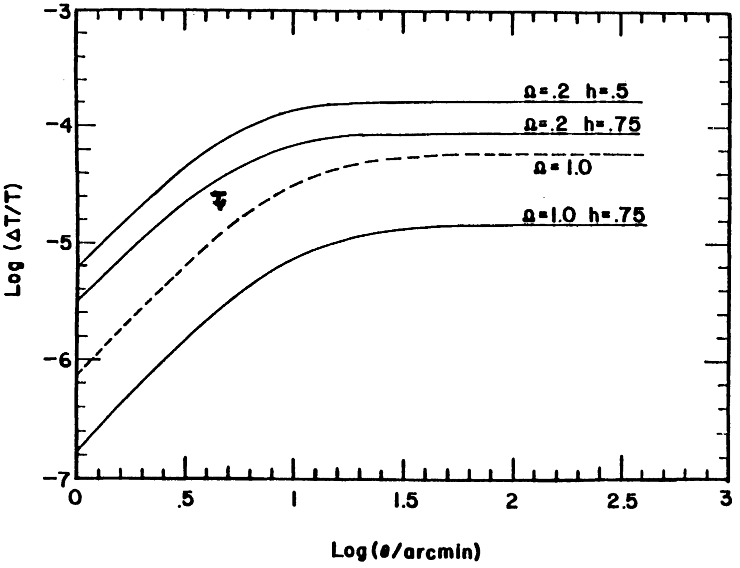

Figure 5. Adapted from Bond and Efstathiou (1984). The predicted amplitude of CBR fluctuations is shown for various cosmological models under the assumption that last scattering occurred at z ~ 1000. Solid curves--models with ρ_0 dominated by cold dark matter. Dashed curve--a model with $\rho_0 = \rho_c$ of hot dark matter, such as massive neutrinos. The observational upper limit is that of Uson and Wilkinson (1985).

consequence, yet another modification to the standard theory of galaxy formation has been introduced--biased galaxy formation, in which galaxies form only in regions of particularly high overdensity, e.g., 2.5σ or 3σ deviations (Bardeen et al, 1986). Since the theoretical predictions of the amplitude of $\Delta T/T$ fluctuations are calibrated by using the present distribution of galaxies (see Bond and Efstathiou, 1984; or Vittorio and Silk, 1984), including bias in effect lowers the predicted amplitude of $\Delta T/T$ by a like factor of ~ 3.

Despite their importance, I have moved rapidly over the consequences of the upper limits on $\Delta T/T$ because they are discussed much more fully by others (e.g., Bond and Efstathiou, 1987). In addition, you will be hearing more about the constraints on theories of galaxy formation from other speakers at this symposium.

Let me now move on to the exciting possibility that fluctuations in the CBR have been detected on angular scales below 1'. If these results are confirmed, they suggest that the material contents of the Universe have been reionized at some redshift below z = 1000, shifting the surface of last scattering to more recent epochs. Although the results are still extremely tentative, it is interesting to note that the amplitude of the fluctuations on scales 0.1-1' are roughly at the level predicted by the preliminary calculations of Ostriker and Vishniac (1986). These predicted amplitudes are derived from simple models of the heating of the intergalactic plasma. At the moment, these arguments and the models included in them are quite general, and both the amplitude and the predicted spectrum of $\Delta T/T$ fluctuations may eventually be modified by more detailed calculations. Nevertheless, it is interesting that the predicted amplitudes in the models which include reionization are roughly comparable to or perhaps slightly larger than the amplitude of fluctuations expected from density perturbations present at z = 1000. Of more interest to the observers, perhaps, is the fact that the predicted amplitudes are within our immediate experimental reach.

4. OTHER OBSERVATIONS AND CONCLUDING REMARKS

Since this is intended to be a general overview of CBR observations, I would like to mention two other sorts of measurements, at least briefly.

4.1. Polarization of the CBR.

This topic will not be mentioned elsewhere in this volume, so let me introduce it briefly. It has been recognized for some time (Negroponte and Silk, 1980; Basko and Polnarev, 1980; see also Tolman, 1985) that large angular scale linear polarization can be introduced into the CBR by anisotropic expansion at the epoch of recombination (or, more generally, at any epoch of last scattering). Observations of, or upper limits on, the linear polarization of the CBR thus provide constraints on possible anisotropic cosmological models which complement direct measurements of $\Delta T/T$. The best upper limits to date are those established by Lubin et al (1983b). The limit on linear polarization is $\leq 3 \times 10^{-4}$. That same paper reports weaker limits also on the circular polarization of the CBR, though these appear to be of less theoretical interest.

There are as yet no sensitive upper limits on small-scale linear polarization which is expected on angular scales slightly less than the ~ 10' angular scale where intensity fluctuations are largest according to many models of galaxy formation (Bond and Efstathiou, 1986). In addition to having slightly smaller angular scales, the polarization fluctuations are expected to have an amplitude roughly one tenth that of the intensity fluctuations--but they may still be measurable because some of the instrumental problems in making searches for intensity fluctuations in the CBR may be avoided.

4.2. Searches for the Sunyaev-Zel'dovich effect

The Sunyaev-Zel'dovich effect (1972) is a small perturbation in the spectrum of the CBR produced by inverse-Compton scattering of photons by hot electrons. If the hot electrons are localized, say in the intergalactic plasma of a cluster of galaxies, a localized temperature perturbation, ΔT, will be produced. In the Rayleigh-Jeans region, this will have a negative sign (see, for instance, the paper by Birkinshaw here). Several groups have searched for this effect in clusters of galaxies (see recent papers by Birkinshaw et al, 1984; Meyer et al, 1983; Radford et al, 1986; Partridge et al, 1987; and references therein). The most reliable of the observational results are those obtained by Dr. Birkinshaw and his colleagues, and those will be discussed by him in this volume. Note also that Dr. Xie will discuss in this volume a novel method for searching for the same effect, this time using an infrared background rather than the CBR. While the small temperature perturbation produced by this effect in clusters of galaxies is not, strictly speaking, a cosmological effect like others described earlier, I mention it for three reasons. First, as pointed out independently by several authors including Gunn (1978), a careful measurement of the Sunyaev-Zel'dovich effect in a cluster of galaxies, combined with X-ray observations of the same cluster, can in principle provide a measurement of Hubble's constant independent of all the steps in the optical distance ladder. This hope has not yet been realized, in part because the microwave background observations are insufficiently accurate, and in part because the best studied clusters do not have good X-ray fluxes or temperature determinations. A second reason for mentioning the Sunyaev-Zel'dovich effect is that the small temperature fluctuations produced by this effect in distant clusters may set limits on our ability to measure cosmological temperature fluctuations from the surface of last scattering (Rephaeli, 1981). A rough calculation I have done suggests that the Sunyaev-Zel'dovich effect may be a more important source of background "fluctuations" than discrete sources, at least at angular scales below an arcminute, but that is a rough calculation which needs refinement.

A final reason for mentioning the Sunyaev-Zel'dovich observations is that they provide a good illustrative example of both the importance and the difficulties of CBR observations. In the case of the Sunyaev-Zel'dovich effect, we can use the observations to tell us about the properties of intergalactic gas in clusters, and possibly also to provide an independent measure of Hubble's constant. Likewise, other observations of the CBR may be used as tools to solve a number of cosmological problems ranging from nucleosynthesis to galaxy formation. As is true in the case of the Sunyaev-Zel'dovich observations, the utility of the CBR observations is largest when they can be combined with other astronomical measurements. One salient example is the power of the constraints set by observations of the abundance of light elements (to be described here by Professor Audouze). As an observer, I would like to add one other common feature--searches for the Sunyaev-Zel'dovich effect, like most of the other observations of the CBR summarized here, are difficult experiments. Some of the difficulties will be summarized in papers following this one by, among others, Halpern, Mandolesi, Davies, Lukash, Birkinshaw and Xie.

I hope this brief overview has given you some idea of the present observational status of the CBR and of the many ways in which the observations may be used in cosmology. I also hope we will be able to meet the challenges over the next few years of improving the measurements and of making further use of the ones we now have.

This paper was prepared while I was a guest of King's College, Cambridge and of the Institute of Astronomy, also in Cambridge. I would like to thank both for their hospitality, and for the opportunity to work both in concert with colleagues and undisturbed by myself. My appearance at this symposium was made possible by a travel grant from the American Astronomical Society, and by funds provided to Haverford College by Bettye and Howard Marshall. The panda cartoons are by Nicholas Bruel, Haverford '87. I would especially like to thank the Local Organizing Committee and the Scientific Organizing Committee for making this symposium so pleasant and fruitful for us all, and to thank the members of the Chinese delegation to this symposium for making me feel so much at home in their midst at the Jia Li Hotel.

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DISCUSSION

TURNER: Concerning the comparison of optical and microwave background peculiar velocity determinations, the optical studies are subject to a bias, related to the Malmquist bias, such that spatial inhomogeneities in the galaxy distribution appear as a peculiar velocity of the observer. This effect discussed by Fall and Jones in 1976 is likely to be particularly severe given the remarkable spatial structures apparent in the CFA "Slice of the Universe" survey and other studies.

SILK: If fluctuations of $\Delta T/T \sim 10^{-4}$ are present on sub arc minute scales in the microwave background, then they are probably too large to be due to fluctuations associated with reionization and galaxy formation. A more plausible-interpretation would invoke a new population of radio sources at high frequency. Could you comment on this?

PARTRIDGE: Let me re-emphasize that the measured values I mentioned are very tentative. Likewise, the predictions of Ostriker and Vishniac (Ap. J. Letters, 306, 1986) are approximate. If we accept both, however, they are consistent if we assume the fluctuations we (may) see are dominated by the smallest angular scales we observe. This is because Ostriker and Vishniac predict values of $\Delta T/T$ which depend on large negative powers of Θ (e.g. $\propto \Theta^{-3}$).

CHEN: Will the interaction between host intergalactic clouds (IGC) and the CBR through the inverse-compton scattering influence the isotropic nature if the IGC distribution is not uniform?

PARTRIDGE: Yes, in addition to possibly perturbing the spectrum of the radiation. This could take two forms - the usual Sunyaev-Zeldovich effect of hot gas concentrated in clusters of galaxies (investigated about five years ago by Rephaeli) and, for larger optical depths, something like the effect discussed in more recent papers by Hogan and by Ostriker and Vishniac. Either could add to purely "cosmic" temperature fluctuations. The problem, of course, is that we haven't reliably detected fluctuations of any sort.